REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggesstions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any oenalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 06-09-2010	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 14-Sep-2009 - 13-Jun-2010

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Multi-Wavelength InAs Quantum Dot Microtube Lasers on Si	W911NF-09-1-0471
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102

6. AUTHORS	5d. PROJECT NUMBER
Zetian Mi	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
McGill University 853 Sherbrooke Street West Montreal, Quebec, QC H3A 2 -T6	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 57303-EL-II.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

In this report, we summarize our work on the design, fabrication, and characterization of multi-wavelength rolled-up quantum dot tube lasers and coherent light sources on GaAs and InP substrates. We also describe the controllable transfer of rolled-up quantum dot tube cavities on Si or any other foreign substrates using fiber abrupt taper assisted transfer technique. The design and fabrication of electrically injected rolled-up quantum dot tube lasers is also presented.

15. SUBJECT TERMS

quantum dot, nanolaser, Si photonics, semiconductor tube, optical cavity

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Zetian Mi
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		19b. TELEPHONE NUMBER 514-398-7114

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Multi-Wavelength InAs Quantum Dot Microtube Lasers on Si

ABSTRACT

In this report, we summarize our work on the design, fabrication, and characterization of multi-wavelength rolled-up quantum dot tube lasers and coherent light sources on GaAs and InP substrates. We also describe the controllable transfer of rolled-up quantum dot tube cavities on Si or any other foreign substrates using fiber abrupt taper assisted transfer technique. The design and fabrication of electrically injected rolled-up quantum dot tube lasers is also presented.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Z. Tian, F. Li, Z. Mi and D. Plant, "Controlled transfer of single rolled-up InGaAs/GaAs quantum dot microtube ring resonators using optical fiber abrupt tapers," Photon. Tech. Lett., vol. 22, pp. 311-313, 2010.

2. Invited: Z. Mi, F. Li, Y.-L. Chang, and J. L. Wang, "High performance quantum dot microtube lasers and nanowire LEDs on Si," ECS Trans. 28(3), 285, 2010.

Number of Papers published in peer-reviewed journals: 2.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

F. Li and Z. Mi, "Multi-wavelength rolled-up InGaAs/GaAs quantum dot microtube lasers," Prof. SPIE, vol. 7591, 759110O (Feb. 2010).

Number of Papers published in non peer-reviewed journals: 1.00

(c) Presentations

1. Invited: Z. Mi and F. Li, "Rolled-up InGaAs/GaAs quantum dot micro– and nanotube lasers," IEEE Photonics Society Winter Topical Meeting 2010, Majorca, Spain, Jan. 11-13, 2010.

2. Invited: Z. Mi and F. Li, "Design and emission Characteristics of semiconductor micro- and nanotube lasers," Photonics North 2010, Niagara Falls, Ontario, Canada, June 1-3, 2010.

3. F. Li, Z. Mi, and P. Poole, "Controlled 1.3-1.55 μm coherent emission from microbelt-like optical cavities formed by rolled-up InAs quantum dot tubes," IEEE Device Research Conference, University of Notre Dame, IN, USA, June 21-23, 2010.

4. F. Li, and Z. Mi, "Fabrication and characterization of free-standing InGaAs/GaAs quantum dot microbelt-like optical resonators," Electronic Materials Conference 2010, Notre Dame, Indiana, USA, June 23-25, 2010.

Number of Presentations: 4.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):   0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):   0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Method for Fabricating Optical Microtubes and Devices Thereof

Patents Awarded

Graduate Students

NAME	PERCENT_SUPPORTED
Feng Li	0.50
Yi-Lu Chang	0.25
FTE Equivalent:	**0.75**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields: 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields: 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME   PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Final Project Report

1. **Title of Project:** "Multi-Wavelength InAs Quantum Dot Microtube Lasers on Si"

2. **Grant Number:** W911NF-09-1-0471

3. **Period Covered by Report:** 09/14/2009 – 06/13/2010

4. **Name of Institution:** McGill University

5. **Principal Investigator:** Zetian Mi

6. **Scientific Progress and Accomplishments:**

- **Introduction**

    Electrically injected nanoscale coherent light sources on Si, with operation wavelengths at 1.3 – 1.55 μm and controlled emission properties, are required for future applications in chip-level optical interconnects. Recently, semiconductor rolled-up microtubes, formed by self-rolling of coherently strained semiconductor heterostructures through controlled release from their host substrates, have emerged as a promising technique for realizing high performance optical microcavity devices. Such microtubes exhibit a number of unique characteristics, including epitaxially smooth surface and a near-perfect overlap between the active medium and the maximum optical field intensity that are often difficult to achieve in photonic crystal, microdisk, or micropillar based optical microcavity devices. Superior quality rolled-up microtubes that incorporate self-assembled quantum dots have been demonstrated on GaAs substrates. It has also been envisioned that the incorporation of quantum dots in such high Q optical microcavities can lead to micro and nanoscale lasers with potentially ultralow or near-zero threshold, temperature invariant operation, and ultrahigh-speed frequency response.

    Optical resonance modes have been first observed in InAs/GaAs quantum dot microtubes at 5 K. More recently, we have achieved strong coherent emission from ultrathin-walled (~ 50 nm) InGaAs/GaAs quantum dot microtubes at room temperature. It has also been demonstrated that their emission characteristics, including the mode profiles, emission direction, and output coupling efficiency, can be controlled by varying the tube diameters, wall thicknesses, as well as the surface geometry using standard photolithography process. To date, however, a rolled-up micro- or nanotube laser has not been demonstrated. Additionally, electrically injected semiconductor tube coherent light sources, as well as the achievement of such devices on a Si platform have not been reported.

    In this report, we summarize our work on the design, fabrication, and characterization of multi-wavelength rolled-up quantum dot tube lasers and coherent light sources on GaAs and InP substrates. We also describe the controllable transfer of rolled-up quantum dot tube cavities on Si or any other foreign substrates using fiber abrupt taper assisted transfer technique. The design and fabrication of electrically injected rolled-up quantum dot tube lasers is also presented.

Accomplishments

- **Optically Pumped Rolled-up InGaAs/GaAs Quantum Dot Tube Lasers**

    Self-organized quantum dot microtube laser heterostructures were first grown on GaAs substrates by solid source molecular beam epitaxy. Illustrated in the inset of Fig. 1(a), the laser heterostructure consists of two InGaAs/GaAs quantum dot layers, a 20 nm pseudomorphic $In_{0.18}Ga_{0.82}As$ quantum well, and a 50 nm AlAs sacrificial layer. Growth conditions for the quantum dot layers were varied in order to achieve a relatively large inhomogeneous broadening without compromising the quality of the dot layers, which can provide large and broad gain. Additionally, the resulting 3-dimensional carrier confinement greatly reduces nonradiative recombination associated with the presence of surface defects. Important considerations in the design of microtube lasers include the photon confinements both around the circumference of the tube as well as along the axial direction. These requirements can be met by utilizing free-standing microtubes with a controlled surface geometry, which can lead to a variation of the effective refractive index along the tube axial direction and therefore appropriate photon confinement for laser operation. The involved fabrication process is briefly described. A U-shaped mesa, shown in Fig. 1(a), was first defined by etching to the InGaAs layer. Quantum dot microtubes with a controlled surface geometry, illustrated in Fig. 1(b), were subsequently formed, when the underlying AlAs sacrificial layer was selectively etched. The surface geometry is directly related to the corrugations introduced at the inner edge of the U-shaped mesa. To reduce the radiative loss through the substrate, the region between the two side pieces of the U-shaped mesa was etched to ~ 1 µm before the tube formation, which further increases the air gap between the central part of the tube and the substrate, shown in Fig. 1(c). In this experiment, the fabricated quantum dot microtubes had approximately two revolutions, corresponding to a wall thickness of ~ 100 nm. The tube diameters are ~ 5 – 6 µm, predetermined by the strain of the pseudomorphic InGaAs layer and the subsequently grown quantum dot heterostructure.

    We have also achieved free-standing microbelt-like optical cavities by embedding a ridge-waveguide in a rolled-up tube structure. In this fabrication process, a U-shaped mesa, as described above, is first defined. A ridge waveguide is then introduced by performing a very shallow (~ 5 nm) etch on the mesa. The widths and lengths of the waveguide vary in the range of 1 – 5 µm and 15 – 30 µm, respectively. The formation of the semiconductor tube creates a belt-like geometry at the tube inner surface (Fig. 2(a)), leading to the unique microbelt-like optical cavity with the confined optical modes precisely controlled by the belt width, height, and length. In this experiment, the tube diameter is ~ 5 µm and the wall thicknesses vary from ~ 50 to 250 nm. The optical microscopy image of free-standing microbelt cavities is shown in Fig. 2(b).
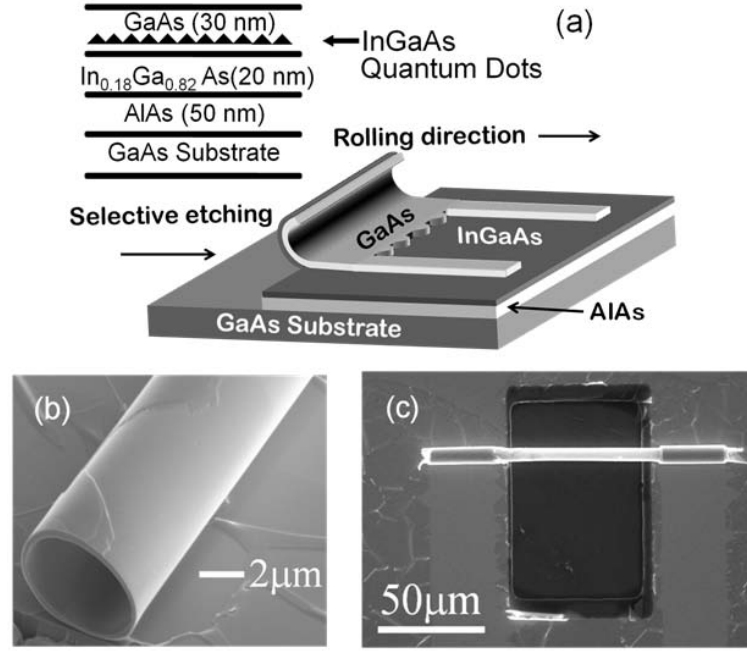
Fig. 1. (a) Schematic illustration of the fabrication of rolled-up free-standing InGaAs/GaAs quantum dot microtubes and the InGaAs/GaAs quantum dot microtube laser heterostructure on GaAs (inset); (b) SEM image of a rolled-up quantum dot microtube with a modified surface geometry; (c) SEM image of a rolled-up quantum dot microtube fabricated on an etched region on GaAs.
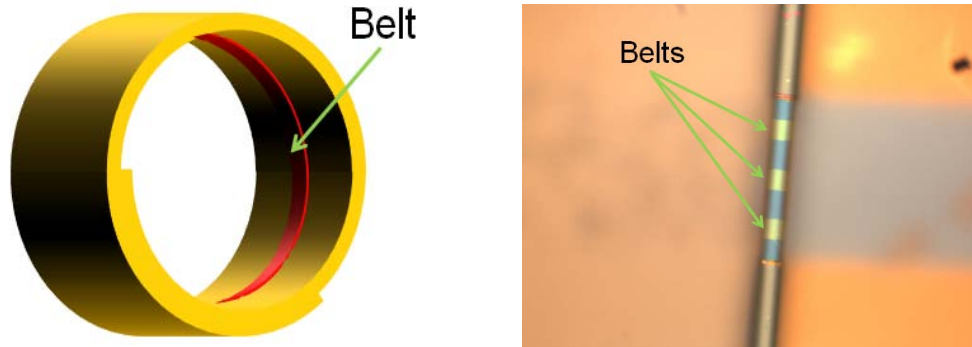

Fig. 2. (a) Illustrations of a microbelt optical cavity; (b) Optical microscope image of free-standing microbelt optical cavities with a belt width of ~ 5 μm.

Rolled-up InGaAs/GaAs quantum dot microtube lasers were characterized using micro-photoluminescence spectroscopy at room temperature. The devices were optically excited by a continuous wave He-Ne laser (λ = 632.8 nm) through a microscope objective. Emission from the microtube was collected by the same objective and analyzed using a high-resolution spectrometer and an InGaAs detector with lock-in amplification. The emission spectrum measured at an absorbed pump power of ~ 3 μW (below threshold) is shown in the inset of Fig. 3(a), which is characterized by a sequence of sharp peaks superimposed on a broad quantum dot emission spectrum in the

wavelength range of 1.1 – 1.3 μm. The observed optical modes, separated by ~ 20 meV, are identified to be the azimuthal modes, which satisfy the phase matching for resonance around the tube circumference. The associated azimuthal mode numbers (*m*) are denoted. With the increase of pump power, the peak intensity increases drastically. Illustrated in Fig. 3(a) are the optical resonance modes associated with the quantum dot ground state transitions measured at a pump power well above the threshold. It is seen that the quantum dot background emission becomes essentially negligible, compared to the peak intensity. The dominant lasing wavelengths are 1193.6, 1216.5, and 1240.7 nm, respectively.
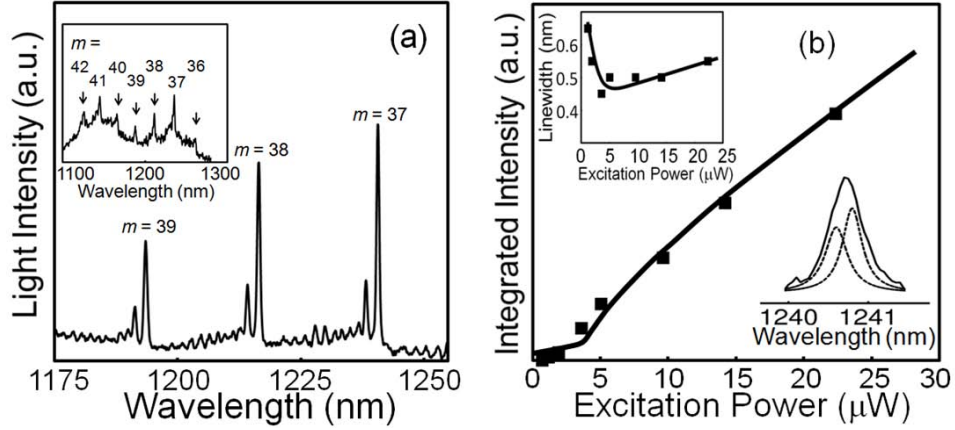
Fig. 3. (a) Emission spectrum of InGaAs/GaAs quantum dot microtube lasers measured at an absorbed pump power of ~ 23 μW (above threshold). The emission spectrum measured at an absorbed pump power of ~ 3 μW (below threshold) is shown in the inset. (b) The integrated light intensity for lasing mode at 1240.7 nm versus absorbed pump power at room temperature. Variation of the linewidth of the mode versus absorbed pump power is shown in the upper inset. A detailed view of the optical resonance mode at ~ 1240.7 nm above threshold and the fit with two Lorentzian curves are shown in the lower inset.
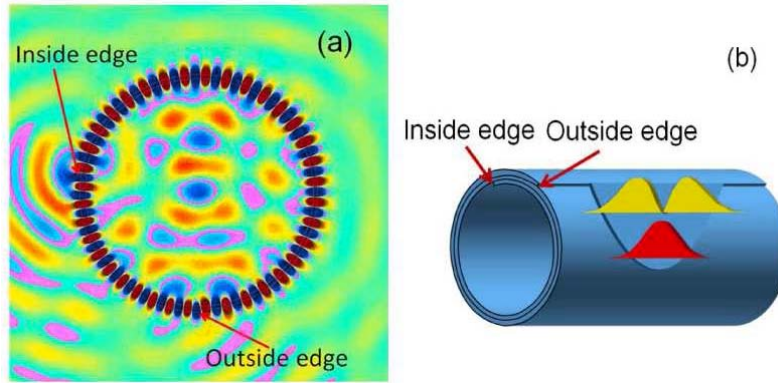

Fig. 4. (a) Distribution of the simulated optical resonance mode at *m*=37 by the finite difference time domain method for a rolled-up microtube with a diameter of 5.6 μm and wall thickness of ~100 nm; (b) Schematic illustrations of the first two axial field distributions associated with each azimuthal mode, due to the optical confinement along this direction.

Variations of the peak intensity versus pump power were also measured. Plotted in Fig. 3(b) is the integrated intensity of the emission peak at 1240.7 nm ($m = 37$) as a function of the pump power, which is the estimated power absorbed by the device. The solid curve is used as a guide to the experimental data points. An extremely low threshold (~ 4 µW) was estimated. Other lasing modes also exhibit similar threshold behavior. The achievement of such a low threshold is attributed to the use of superior quality quantum dot layers in the active region as well as the very small optical loss in the cavity, due to the epitaxially smooth tube surface. From detailed experimental and theoretical analysis, it has been confirmed that coherent emission from the microtube device takes place primarily at the inside edge of the tube. In this experiment, the microtube was formed such that the inside edge was positioned away from the top of the tube, where light emission was collected. Consequently, only a very small portion of the emitted photons were detected when the device was pumped above threshold. This is believed to be the primary reason for the observed "soft" threshold behavior. The variation of the spectral linewidth versus pump power for the same lasing mode was shown in the inset of Fig. 3(b). The linewidth decreases from $\sim 0.6 - 0.8$ nm to approximately $0.4 - 0.5$ nm with the increase of the pump power, due to the increase of temporal coherence. The reduction of the spectral linewidth is in excellent agreement with the measured light-light characteristics, clearly confirming the achievement of lasing in rolled-up InGaAs/GaAs quantum dot microtubes. A small increase of the spectral linewidth with the increase of excitation power is seen, potentially due to heating effect. Also illustrated in Fig. 3(b) is a detailed view of the optical resonance mode at ~ 1240.7 nm above threshold. It is seen that the mode is highly asymmetric. In rolled-up tube structures, due to the spiral symmetry associated with the presence of inside and outside edges, each azimuthal resonance mode is broken into two nondegenerate ones. By fitting the peak using two Lorentzians, we derived an intrinsic spectral linewidth of $\sim 0.2 - 0.3$ nm, which is largely limited by the resolution of the spectrometer used in this experiment.

The confined optical modes in rolled-up microtube lasers were studied using the finite-difference time domain method. Shown in Fig. 4(a) are the simulated azimuthal mode profiles for photons ($m = 37$) confined in a rolled-up tube with a diameter of ~ 5.6 µm and wall thickness of ~ 100 nm. It is seen that coherent emission from rolled-up microtubes is predominantly determined by the photon scattering occurred at the inside edge. The calculated Q-factor is $> 14,000$, which is primarily limited by the optical scattering at the inside and outside edges and, in practice, any irregularities on the surface of the tube as well. This unique phenomenon is enormously important for achieving micro- and nanoscale lasers with controlled emission direction and output efficiency that are generally difficult to realize using photonic crystal, microdisk, and toroidal based optical cavities.

- **1.55 µm Rolled-up InAs/InP Quantum Dot Tube Coherent Light Sources**

To achieve 1.55 µm nanoscale coherent light sources, we have further investigated InAs/InP quantum dot tube device, shown in Fig. 5(a), which consists of a tensile strained $In_{0.68}Ga_{0.32}As_{0.41}P_{0.59}$ layer and an $InAs/In_{0.81}Ga_{0.19}As_{0.41}P_{0.59}$ quantum dot layer on InP substrate. InAs/InGaAsP tubes were formed when the underlying InP sacrificial layers were selectively etched, due to the relaxation of strain (inset of Fig. 5(a)). The device fabrication and measurement process follows that described for 1.3 µm InAs/GaAs quantum tube lasers.

Shown in Fig. 5(b) are the measured emission spectra of InAs/InP quantum dot based optical cavities, which exhibit sharp optical modes in the wavelength range of ~ 1.55 µm at room

temperature. It is important to note that this is the first demonstration of InP based semiconductor tube cavities. These devices exhibit single axial mode operation. The azimuthal mode separation, determined by the tube diameter, is ~ 16.5 meV. It is also seen that the coherent emission is primarily TE polarized, with the electrical field parallel to the belt, or tube surface. Work is currently in progress to demonstrate lasing in rolled-up InAs/InP quantum dot tube optical cavities.
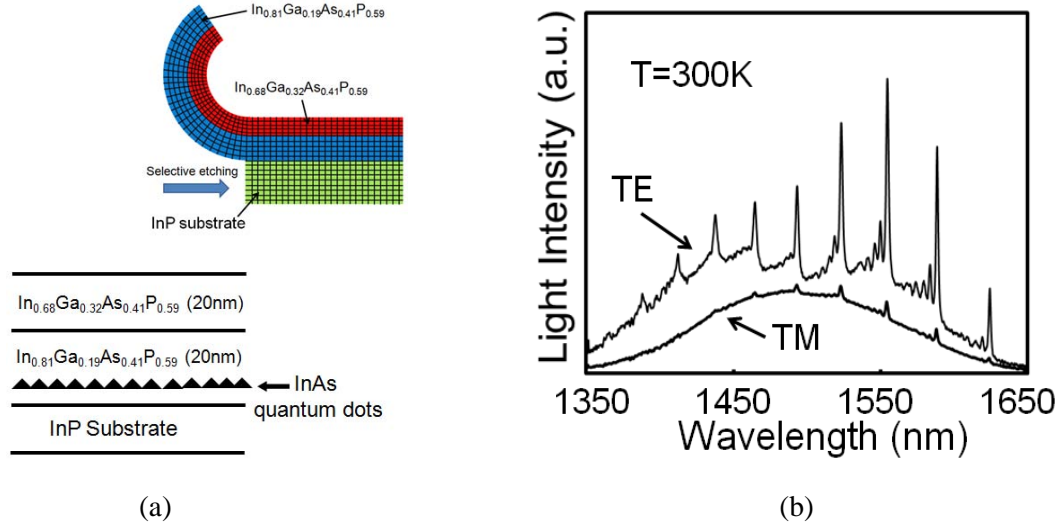

(a)   (b)

Figure 5: (a) Schematic band diagram of the 1.3 µm p-doped tunnel injection quantum dot laser active region, (b) GaAs/AlGaAs heterostructure, and (c) room temperature photoluminescence spectra.

- **Fabrication of Electrically Injected Rolled-up Quantum Dot Tube Coherent Light Sources**

The design and fabrication of electrically injected rolled-up microtube devices on GaAs is described. The electrically injected device heterostructure, shown in Fig. 6(a), is similar to the optically pumped one, except that the top GaAs and the strained InGaAs layers are doped with Si and Be, respectively. Self-organized InGaAs quantum dot layers are incorporated in the GaAs layer as the gain media. During the fabrication process, a U-shaped mesa was first defined using standard photolithography and wet etching techniques, followed by the deposition of the n-metal contact layer on the two side-pieces of the mesa, illustrated in Fig. 6(b). Free-standing rolled-up microtube structures are then fabricated using the same approach described above. Subsequently, an SU-8 passivation and planarization layer, with a thickness of ~ 4 – 5 µm, was spin-coated on the wafer. P-metal contact is deposited in regions of the free-standing microtube where the SU-8 is selectively removed, illustrated in Fig. 6(c). The optical microscopy image of an electrically injected rolled-up microtube device is shown in Fig. 7, wherein the free-standing microtube and p- and n-metal contacts can be identified. The SEM image of the p-metal contact and the free-standing microtube region is shown in the inset of Fig. 7. In this design, electrons and holes are injected directly from the supporting side-pieces and the top surface of the free-standing microtube, respectively. The radiative recombination of charge carriers in the quantum dot active region leads to the emission of photons, which can be largely confined in the micro-tube ring resonator. Electrical and optical properties of such unique electrically injected devices are being investigated.
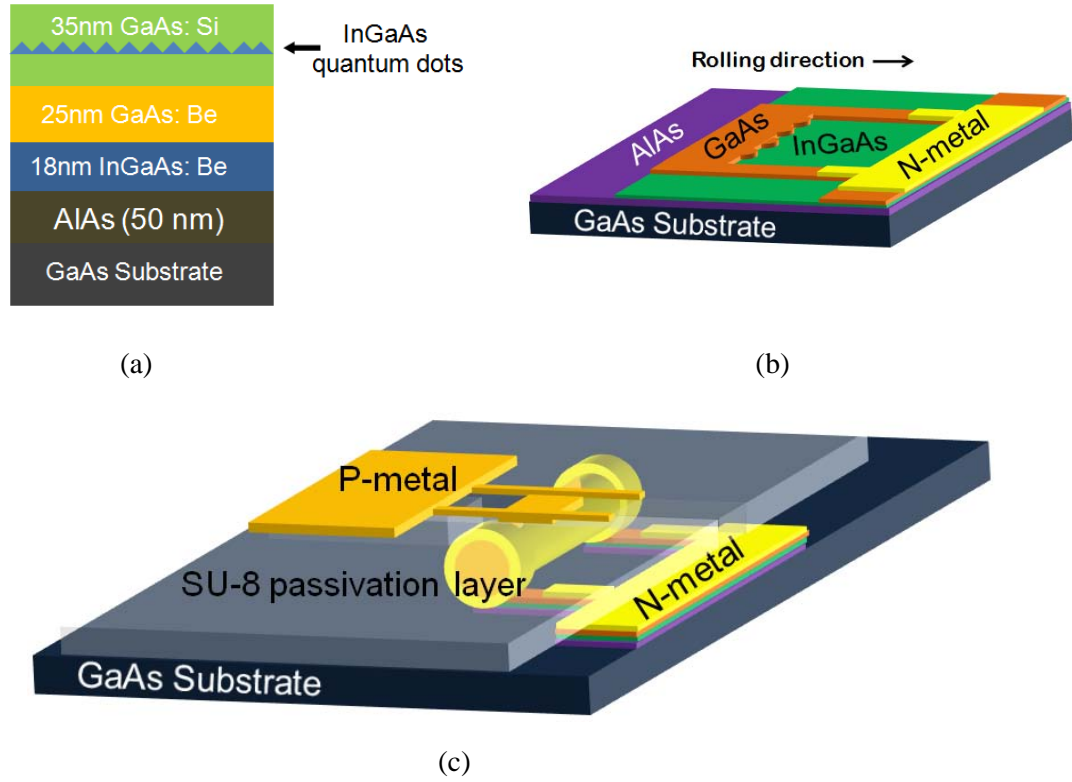
(a)

(b)

(c)

Fig. 6: (a) Schematic illustration of the InGaAs/GaAs quantum dot heterostructure on GaAs for realizing electrically injected microtube devices. (b) and (c): Illustrations of the fabrication processes of electrically injected InGaAs/GaAs quantum dot microtube devices. SU-8 is used as the passivation layer, and the p-metal contact is placed directly on the microtube top surface.
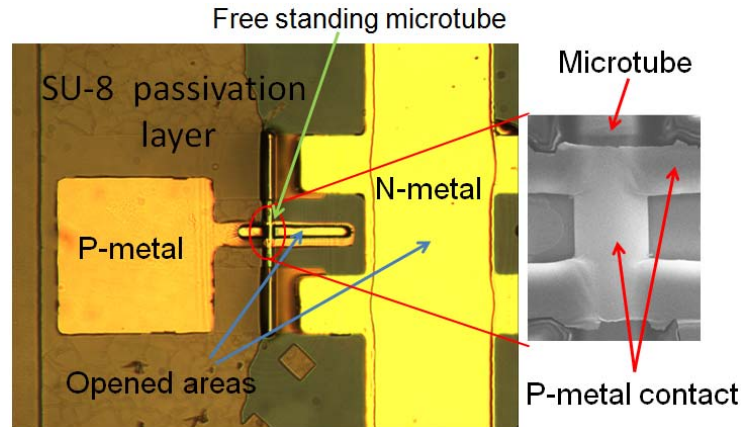

Fig. 7. Optical microscopy image of an electrically injected InGaAs/GaAs quantum dot microtube device. The SEM image of the device active region, including the p-metal contact and the free-standing microtube, is shown in the inset.

- **Controlled Transfer of Single Rolled-up InAs/GaAs Quantum Dot Microtube Ring Resonators Using Optical Fiber Abrupt Tapers**

The controlled transfer and exact positioning of a III-V micro- or nanoscale laser on a processed CMOS chip and their subsequent integration with Si bus waveguides and modulators is in demand for next generation chip-level optical interconnects. In spite of the significant progress made in dry printing, wafer bonding, solution casting, and more recently substrate-on-substrate transfer processes, the reliable transfer of a high quality optical microcavity on a foreign substrate has hitherto not been reported. This has been limited, to a large extent, by the unique properties of III-V optical micro- and nanocavities, which generally relies on the use of free-standing nanomembranes. Consequently, the commonly used dry printing and/or stamping techniques may significantly alter the structural and optical properties of the devices. The presence of a large surface tension for conventional photonic crystal, microdisk, and micropillar devices also makes it extremely difficult to detach the cavities from the handling substrate. Rolled-up semiconductor micro- and nanotubes can be controllably released from the handling GaAs substrate by selectively etching the underlying sacrificial layer. We have recently developed a highly accurate and flexible technique for transferring single rolled-up micro- and nanotube devices. InGaAs/GaAs quantum dot microtubes, with diameters of ~ 5 μm, wall thicknesses of ~ 50 nm, and lengths of > 100 μm, are first picked up using fiber abrupt tapers from the handling GaAs substrates. They are subsequently transferred, with a precisely controlled position, directly on the facet of a single-mode fiber. Detailed studies also confirm that the resulting microtube optical cavities are relatively free of structural defects and exhibit strong coherent emission at room temperature, thereby promising integrated micro- and nanoscale lasers with greatly simplified packaging.

To achieve controlled transfer of the microtube devices, optical fiber abrupt tapers, made by a fusion splicer machine were used in this experiment. The abrupt taper was made asymmetric for the convenience of the transfer process. Two abrupt tapers were mounted on two nanopositioning stages, respectively. The taper tips were inserted at both ends of a microtube device, illustrated in Fig. 8(a). The alignment process can be precisely controlled, since the tube diameter (~ 5 μm) is larger than the size (~ 2 μm) of the taper tip. Subsequently, each taper tip was moved up in a 10 μm step alternatively until the microtube can be fully released from the handling substrate. Due to the presence of a very small contact area between the free-standing microtube devices and the GaAs substrate, the surface tension is much smaller, compared to conventional planar devices. Consequently, detaching the microtube devices from the host substrate can be achieved without introducing any structural defects and/or mechanical distortion. Such microtubes can be controllably transferred using either one or two fiber tapers and precisely positioned on a foreign substrate. Fig. 8(b) shows an optical microscopy image of a microtube device attached to a fiber taper during the transfer process. The SEM image is shown in the inset.

In the transfer experiment, the cleaved facet of a single-mode fiber (Corning SMF-28) was used as the target substrate. The coating of the fiber was stripped and the diameter of the fiber was ~ 125 μm. The fiber facet was coated with a thin (~ 50 nm) layer of Au to facilitate the subsequent SEM studies. Shown in Fig. 9(a) is the optical microscopy image of an InGaAs/GaAs quantum dot microtube transferred directly on the Au-coated facet of a fiber. The SEM image of part of the microtube is shown in the upper inset. An extremely smooth surface, without the presence of any structural defects, can be clearly seen. Although such devices were attached to the fiber facet with

only a limited contact area, the resulting surface tension was strong enough to hold the devices in place, which is further evidenced by the tube attached to the edge of fiber, shown in the lower inset of Fig. 9(a). The controllability and reproducibility of the present transfer technique is further demonstrated by the "M" pattern, shown in Fig. 9(b), which consists of four microtubes transferred on the fiber facet in sequence. The lateral positioning resolution is ~ 1 μm, limited largely by the resolution of the positioning stages used in this experiment.

Emission characteristics of microtube devices transferred on the fiber facet were studied by micro-photoluminescence spectroscopy at room temperature. The device was optically pumped using a He-Ne laser (λ ~ 632.8 nm) through a 60$\times$ objective lens, and the emission was analyzed by a high-resolution spectrometer with lock-in amplification. The output spectrum measured under an absorbed pump power of ~ 20 μW is shown in Fig. 10. The observed resonance modes are directly related to the photon confinements around the circumference of the tube as well as along the tube axial direction. Through detailed analysis using both the finite difference time domain method and also a planar dielectric waveguide model, we can divide the resonance modes into 5 groups. The optical modes within each group have the same azimuthal mode number (m), which is determined by the optical resonance conditions for photons propagating around the circumference of the tube. In addition, the photon confinement along the tube axial direction, due to the presence of surface corrugations, gives rise to various axial field distributions and, consequently, different eigenmodes (p =0, 1, and 2) for each mode m. The associated mode numbers (m and p) for each resonance mode are identified. The energy separations for the dominant modes between two adjacent groups and for the two adjacent modes within the same group are ~ 26 meV and 7.5 meV, respectively, which agree well with our calculations. The measured spectral linewidths are ~ 1 nm, corresponding to a Q-factor of ~ 1,100. The intrinsic Q-factor may be significantly higher, due to the presence of two non-degenerate modes induced by the inside and outside edges around the tube and can be further improved by optimizing the design and fabrication process. The emission characteristics of quantum dot microtubes transferred on the cleaved facet of a fiber are nearly identical, in terms of both the mode profiles and light intensity, to those of similar quantum dot microtube devices fabricated directly on GaAs substrates, which further confirms the present fiber taper assisted transfer technique is suitable for achieving high quality micro- and nanotube based optical cavities on a foreign substrate.
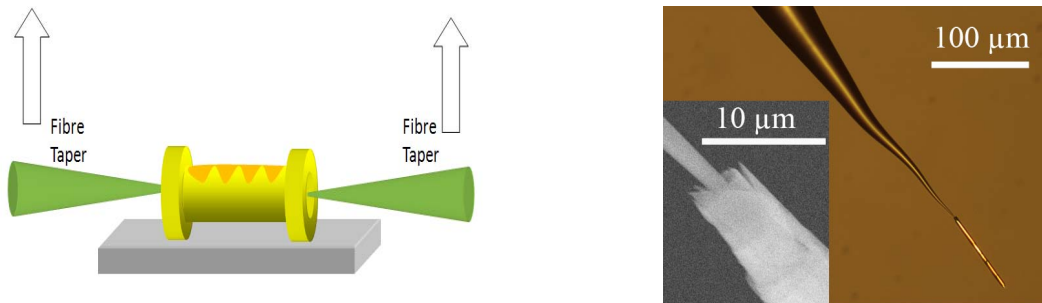

Fig. 8. (a) Illustration of the lift off of a microtube device from the handling GaAs substrate using fiber abrupt tapers by inserting the fiber tips into both ends of the tube and alternatively raising the height of each fiber tip by a small step. (b) Optical microscopy image of an InGaAs/GaAs quantum dot microtube attached to the tip of a fiber during the transfer process and the corresponding scanning electron microscopy image (inset).
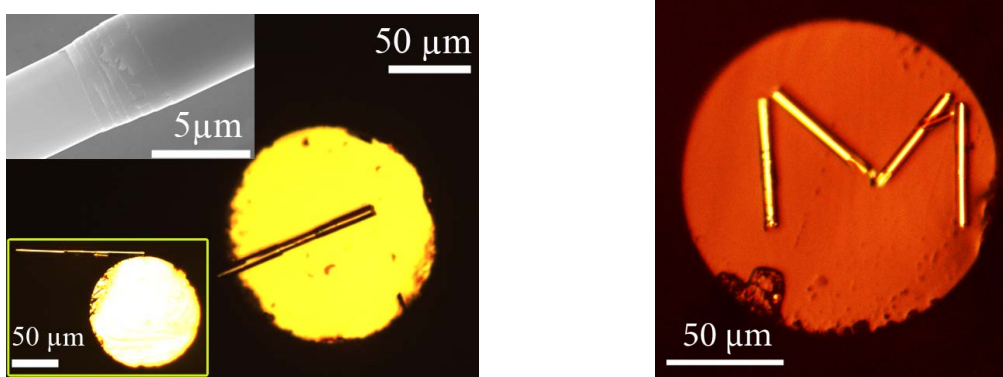
Fig. 9. (a) Optical microscopy image of a rolled-up InGaAs/GaAs quantum dot microtube transferred onto the cleaved facet of a single-mode fiber and also a microtube attached to the edge of the fiber (lower inset). The SEM image of the tube on the fiber is shown in the upper inset. (b) An "M" pattern made of four rolled-up microtubes transferred on the cleaved facet of a single-mode fiber.
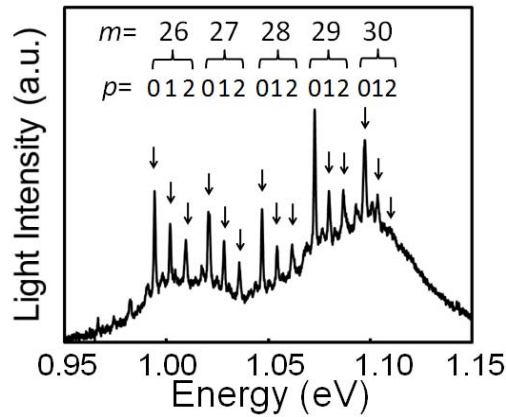

Fig.10. Emission spectrum of a rolled-up InGaAs/GaAs quantum dot microtube transferred on the cleaved facet of a single-mode fiber measured under an absorbed pump power of ~ 20 µW at room temperature.

Finally, it is important to note that emission from the rolled-up tube cavity devices can also be directly coupled to the optical fiber, with the coupling efficiency precisely determined by the vertical separation, or the number of resolutions of the microtube sidepieces. With the development of the fiber taper assisted transfer technique, it is also expected that nearly defect-free III-V micro- and nanotube based nanophotonic devices can be readily achieved on any foreign substrates. More importantly, it provides a viable approach for the monolithic integration of high performance III-V semiconductor micro- and nanoscale lasers with Si waveguides and other nanophotonic devices on CMOS chips.

In summary, we have demonstrated a powerful approach, combining both rolled-up microtubes and the fiber abrupt taper assisted transfer technique, for achieving high quality single III-V optical

micro and nanocavities on the facet of a single-mode fiber with a precisely controlled position. The present transfer process can be carried out at room temperature in an ambient environment and, therefore, may enable the achievement of a new class of micro- and nanoscale lasers on virtually any substrates for future integrated, multi-functional nanophotonic systems.

7. List of Publications

1. "Controlled coherent emission from microbelt-like optical cavities formed by rolled-up InAs quantum dot tubes," P. Bianucci, F. Li, and Z. Mi, in preparation.

2. "Multi-wavelength InAs/InP quantum dot tube coherent light emitting devices," P. Bianucci, S. Mukherjee, and Z. Mi, in preparation.

3. Z. Tian, F. Li, Z. Mi and D. Plant, "Controlled transfer of single rolled-up InGaAs/GaAs quantum dot microtube ring resonators using optical fiber abrupt tapers," *Photon. Tech. Lett.*, vol. 22, iss. 5, pp. 311-313, 2010.

4. F. Li, Z. Mi, and P. Poole, "Controlled 1.3-1.55 µm coherent emission from microbelt-like optical cavities formed by rolled-up InAs quantum dot tubes," *IEEE Device Research Conference*, University of Notre Dame, IN, USA, June 21-23, 2010.

5. F. Li, and Z. Mi, "Fabrication and characterization of free-standing InGaAs/GaAs quantum dot microbelt-like optical resonators," *Electronic Materials Conference 2010*, Notre Dame, Indiana, USA, June 23-25, 2010.

6. Invited: Z. Mi and F. Li, "Design and emission Characteristics of semiconductor micro- and nanotube lasers," *Photonics North 2010*, Niagara Falls, Ontario, Canada, June 1-3, 2010.

7. Invited: Z. Mi, F. Li, Y.-L. Chang, and J. L. Wang, "High performance quantum dot microtube lasers and nanowire LEDs on Si," *217th Electrochemical Society Meeting*, Vancouver, Canada, April 25-30, 2010.

8. F. Li and Z. Mi, "Multi-wavelength rolled-up InGaAs/GaAs quantum dot microtube lasers," *SPIE Photonics West Conference*, San Francisco, CA, Jan. 23-28, 2010.

9. Invited: Z. Mi and F. Li, "Rolled-up InGaAs/GaAs quantum dot micro– and nanotube lasers," *IEEE Photonics Society Winter Topical Meeting 2010*, Majorca, Spain, Jan. 11-13, 2010.

8. Report of Inventions

None.

9. List of Scientific Personnel Supported, Degrees, Awards and Honors

Zetian Mi received the Hydro-Quebec Nano-Engineering Scholar Award from McGill University in 2009.

Zetian Mi will receive the Young Investigator Award from North American Molecular Beam Epitaxy Conference in Sep. 2010.

10. Technology Transition

None.